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Optimization of Dump Truck and Excavator Usage for Earthwork Activities using Genetic Algorithm Method

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Abstract. Earthmoving activities constitute a fundamental component of infrastructure development, particularly in large-scale projects such as the construction of the Presidential Palace at Indonesia's new capital city (Ibu Kota Nusantara/IKN). The effectiveness and efficiency of these operations are highly dependent on the optimal selection and combination of heavy equipment, notably excavators and dump trucks. The challenge lies in the complexity of multiple variables, including equipment capacity, operational speed, fuel consumption, and both fixed and variable costs. Conventional selection methods—often relying on manual calculation, managerial intuition, and trial-and-error—are limited in addressing these multidimensional considerations. This study proposes a computational model utilizing a Genetic Algorithm (GA) to optimize equipment configuration by minimizing project duration and operational costs. The model integrates various technical and economic parameters into two main objective functions: Activity Time (AT) and Activity Cost (AC). The GA's capability to efficiently explore large solution spaces and handle multi-objective problems provides a significant advantage over traditional approaches. A case study was conducted on the earthmoving operations of the Presidential Palace construction project, involving 55,052 m³ of soil and a 2.5 km hauling distance. The optimal configuration—comprising 3 excavators and 3 dump trucks operating at a speed of 25 km/h—achieved a project duration of 414.36 hours, a 30% reduction compared to the actual duration (592 hours), and a total cost of IDR 2,790,976,831, which is approximately 1.2% lower than the actual project cost. These results highlight the GA model's effectiveness in producing more efficient and cost-effective equipment configurations. The proposed method offers valuable decision-making support for project managers and contractors seeking to improve the planning and execution of earthwork activities through systematic optimization.

Introduction

Earthwork plays a pivotal role in large-scale construction projects, particularly in the early phases of infrastructure development such as roads, dams, and governmental buildings. A prime example is the development of the Presidential Palace at Indonesia's newly designated capital, Ibu Kota Nusantara (IKN), which forms part of a strategic national agenda mandated by Law No. 3 of 2022 concerning the relocation of the capital from Jakarta to East Kalimantan.

Among the foundational activities in this project is large-volume earthmoving, involving extensive excavation and backfilling tasks. These operations heavily rely on heavy construction machinery, primarily excavators for excavation and dump trucks for transporting material. The operational efficiency of such equipment configurations directly influences project timelines, fuel usage, labor productivity, and overall cost performance. Suboptimal selection of equipment combinations may result in project delays, excessive fuel consumption, and inflated operating costs. Despite these consequences, equipment planning is frequently based on conventional approaches such as professional judgment, empirical estimates, or manual calculations. These traditional techniques, while practical, are often inadequate for tackling the intricate interactions among technical and economic variables in large-scale projects. With the advancement of computational tools, optimization-based techniques have emerged as a viable alternative for addressing equipment management challenges in construction. Among these, the Genetic Algorithm (GA) stands out as a robust metaheuristic inspired by the principles of natural selection. GA has demonstrated effectiveness in resolving complex, nonlinear, and multi-objective problems across various domains, including project scheduling, equipment selection, and resource allocation. Prior studies, such as that by Shehadeh et al. (2022), have shown that GA can significantly enhance productivity and cost-efficiency in earthmoving by integrating diverse parameters into a structured optimization model.

Building upon this foundation, the present study introduces a GA-based model to optimize the selection of heavy equipment for the earthwork component of the Presidential Palace project at IKN. The model considers multiple variables—such as equipment capacity, fuel consumption, cycle time, and cost components—by formulating two core objectives: minimizing project duration and minimizing operational costs. The model's applicability is tested through a real-world case study, offering insights for project managers seeking more efficient and sustainable construction practices. The main contribution of this research is the development of a multi-objective optimization framework that can be adapted to various project types, particularly those facing constraints in cost, time, or resource availability. The case study from the IKN Presidential Palace construction reinforces the model's practical value and potential scalability.

Method

Research Location and Object. This study was conducted in the construction area of the Presidential Palace located in the new capital city of Indonesia, Ibu Kota Nusantara (IKN), specifically in North Penajam Paser Regency, East Kalimantan Province. The project is part of a national strategic initiative as stipulated in Law Number 3 of 2022. The main activity analyzed in this study involves large-scale earthwork operations, including soil excavation and hauling over a distance of approximately 2.5 kilometers, with a total soil volume of 55,052 cubic meters.

Research Type and Approach. A quantitative approach was employed in this study, utilizing the Genetic Algorithm (GA) as the optimization technique. GA was chosen due to its ability to handle complex problems involving multiple variables without requiring an explicit mathematical formulation. It mimics the natural selection process through stages such as selection, crossover, and mutation, enabling effective exploration of the solution space and convergence toward near-optimal solutions.

Data and Research Variables. The data used in this research were sourced from both primary and secondary means. Primary data were obtained from field observations on the construction site, while secondary data were gathered from literature, technical manuals, and equipment specifications. The data were categorized into three main groups: (1) equipment specifications, including bucket capacity, dump truck capacity, fuel consumption, operational speed, and cycle time; (2) cost data, comprising fixed costs (rental and maintenance) and variable costs (fuel consumption and tire replacement); and (3) operational parameters such as tool efficiency, hauling distance, and project volume.

In the context of earthwork optimization, there are five main variables that influence project duration and cost: the number of excavators, the number of trucks, excavator capacity, truck capacity, and truck speed. **Table 1** presents these five design variables (along with their notations) used to formulate the mathematical optimization model for earthmoving activities. Among these, truck speed is considered a critical factor as it directly affects fuel consumption, tire wear, and project duration. Higher speed may reduce execution time but increase operational costs, whereas lower speed may save fuel but lengthen the duration. Thus, truck speed must be carefully considered to strike a balance between time and cost efficiency.

Table 1. Description of Design Variables

Decision Variable	Notation	Description
Number of excavators	Nle	Has a maximum limit to avoid delays caused by truck queuing.
Number of dump trucks	NTP	Depends on the maximum number of excavators.
Excavator capacity	Ec	Can be determined from the manufacturer's handbook (m^3).
Dump truck capacity	Tip	Can be determined from the manufacturer's handbook (m^3).
Truck operating speed	Es	Has minimum and maximum values based on DOT standards and the manufacturer's handbook (km/h).

Optimization Model Formulation. The optimization model was built on two objective functions:

1. Minimization of Activity Time (AT):

$$AT = \frac{Tpq \times Tct \times Es + 60 \times Md \times Ec \times Bff \times Ef \times Nle}{60 \times Ec \times Bff \times Es \times Nle}$$

Where:

The model variables include: AT (Activity Time in hours), Tpq (Total Project Volume in m^3), Tct (Cycle Time), Es (Truck Speed in km/h), Md (Hauling Distance in km), Ec (Excavator Capacity in m^3), Bff (Bucket Fill Factor), Ef (Excavator Efficiency), and Nle (Number of Excavators).

2. Minimization of Activity Cost (AC):

$$AC = AT \times ((Nle \times Ce) + (NTP + Ct))$$

Where:

The cost-related variables in the model include: AC (Activity Cost in IDR), Nle (Number of Excavators), Ce (Excavator Cost per Hour), NTP (Number of Dump Trucks), and Ct (Dump Truck Cost per Hour). These functions consider equipment efficiency, fuel cost, service, tire replacement, and hauling time.

Genetic Algorithm Application. The optimization model formulated in this study incorporates two main objective functions: minimizing the project duration (Activity Time/AT) and minimizing total project cost (Activity Cost/AC). The time function calculates the required duration based on the total excavation volume, equipment capacity, operational efficiency, and cycle time. Meanwhile, the cost function is based on the total hourly equipment cost multiplied by the total project time. GA is applied to iteratively evaluate various combinations of equipment usage. The process begins by generating an initial population consisting of random equipment combinations, each treated as a chromosome. Chromosomes are evaluated using the objective functions. The selection process is carried out using the roulette wheel method, followed by crossover operations to produce new combinations and random mutations to maintain diversity. This process continues over multiple generations until an optimal or near-optimal solution is achieved.

Model Validation. To validate the model's accuracy, the optimization results were compared with actual operational data from the IKN construction site. The field configuration used two KOBELCO SK 200 excavators with a bucket capacity of 0.8 m³ and two Hino Ranger FM 260 JD dump trucks with a loading capacity of 18 m³. The fuel consumption for each machine was 13.74 liters/hour for the excavators and 12.39 liters/hour for the dump trucks. Equipment rental costs were Rp 781,440 per hour for the excavators and Rp 546,480 per hour for the dump trucks. The tire replacement cost for the dump truck was Rp 48,000,000 with an estimated lifespan of 3,000 operational hours. Diesel fuel was priced at Rp 17,500 per liter. Due to site conditions, the average dump truck speed was recorded at 30 km/h. Based on this configuration, the project was completed in 592 hours with a total cost of Rp 2,825,079,204. **Table 2** and **3** summarize the detailed input data and equipment specifications used in the model.

Table 2. Project and Contract Condition Data

Input Data	Notation	Value
Total project volume (m³)	Tpq	55052 m3
Bucket fill factor for Excavator	Bff	0.8
Service cost percentage	Psc	19%
Hauling distance (km)	Md	5 km

Table 3. Input Data of Equipment Used

Input Data	Notation	Excavator (KOBELCO SK 200)	Truk (Hino Ranger Dump FM 260 JD)
Fixed Operating Cost (Rp/hour)	DC	Rp 781,440.00	Rp 546,480.00
Fuel Price (Rp/liter)	Up	Rp 17,500.00	Rp 17,500.00
Fuel Consumption per Hour (liter/hour)	Fce / Fct	13,74	12,39
Equipment Capacity (m³)	Lc / Tic	0,8	18
Tire Replacement Cost (Rp)	Rct	–	Rp 48,000,000.00
Tire Lifespan (operating hours)	OLc	–	3000
Maximum Speed (km/hour)	Ms	–	87
Operational Speed (km/hour)	Es	–	30
Total Project Cost (Rp)	TCP	–	Rp 2,825,079,204.00
Total Project Duration (hours)	TDP	–	592

Results and Discussion

Optimal Trade-Off Between Cost and Time. This study explores several solutions for combinations of heavy equipment—consisting of the number of trucks, number of excavators, truck bed capacity, excavator bucket capacity, and truck speed—to optimize the project duration and cost for an earthmoving project with a total volume of 55,052 m³. The simulation results were compared with the actual project data, which had an activity time of 592 hours and an activity cost of Rp2,825,079,204. In Combination 1, Solution 1, which used 8 trucks and 5 excavators with a truck speed of 15 km/h, resulted in a project duration of 299.81 hours, or 49.4% faster than the actual data. However, the cost increased to Rp3,456,114,163.59, or about 22.3% higher, indicating that time acceleration comes with a significant cost increase. This solution is suitable for projects that prioritize shorter completion time and can tolerate higher costs. Solution 2, using 6 trucks and 4 excavators with a speed of 20 km/h, achieved a duration of 334.77 hours (43.5% faster) with a cost of Rp3,062,448,304.39, an 8.4% increase from the actual cost. This suggests a better balance between time and cost efficiency compared to Solution 1. Next, Solution 3, with 4 trucks and 3 excavators at a truck speed of 30 km/h, resulted in a duration of 393.09 hours (33.6% faster) and a cost of

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Rp2,682,859,343.53, which is 5% lower than the actual cost. This configuration demonstrated simultaneous cost and time efficiency. In contrast, Solutions 4 and 5 in Combination 1 showed a drastic decline in efficiency. Solution 4 had a duration of 589.55 hours, nearly equal to the actual time, but at a cost of Rp3,424,808,458.12 (an increase of 21.2%). Solution 5 had a duration of 1,133.41 hours and a cost of Rp3,886,791,185.60, indicating that a drastic reduction in heavy equipment leads to inefficiency despite the assumed cost savings. A similar pattern was observed in Combination 2. Solution 1, with 7 trucks and 5 excavators at 15 km/h, yielded a duration of 299.81 hours (49.4% faster) and a cost of Rp3,243,124,772.69 or 14.8% higher than the actual cost. Solution 2, using 5 trucks and 4 excavators at 20 km/h, achieved a duration of 334.77 hours (43.5% faster) with a cost of Rp2,824,621,536.64, almost equal to the actual cost. Interestingly, Solution 3, with 3 trucks and 3 excavators at 25 km/h, produced a duration of 414.36 hours (30% faster) and a cost of Rp2,510,103,428.68, which is 11.1% lower than the actual cost—making it the most optimal solution in terms of both time and cost efficiency. Conversely, Solutions 4 and 5 again showed reduced efficiency. Solution 4 had a duration of 589.55 hours and a cost of Rp3,005,974,864.37, while Solution 5 had the longest duration of 1,178.94 hours with a cost of Rp3,138,348,075.37. These findings indicate that reducing the number of heavy equipment units can lower costs to some extent, but excessive reductions lead to significantly longer durations and still high costs.

Overall, the trade-off between cost and time offers a variety of alternative solutions that can be chosen depending on project priorities—whether prioritizing time efficiency, cost efficiency, or a balanced compromise. In summary, the analysis shows that increasing the number of equipment units can accelerate completion time but significantly raises costs, while reducing equipment excessively results in extended duration and inflated cost. The most optimal solution was found in Solution 3 of Combination 2, which balanced a 30% reduction in project duration with a 1.2% cost saving compared to actual data. The optimal combination is shown in **Fig. 1**, reinforcing the importance of multi-objective optimization in selecting appropriate heavy equipment combinations to enhance the efficiency and effectiveness of earthmoving construction projects.The selected optimal solutions are summarized in **Table 4**.

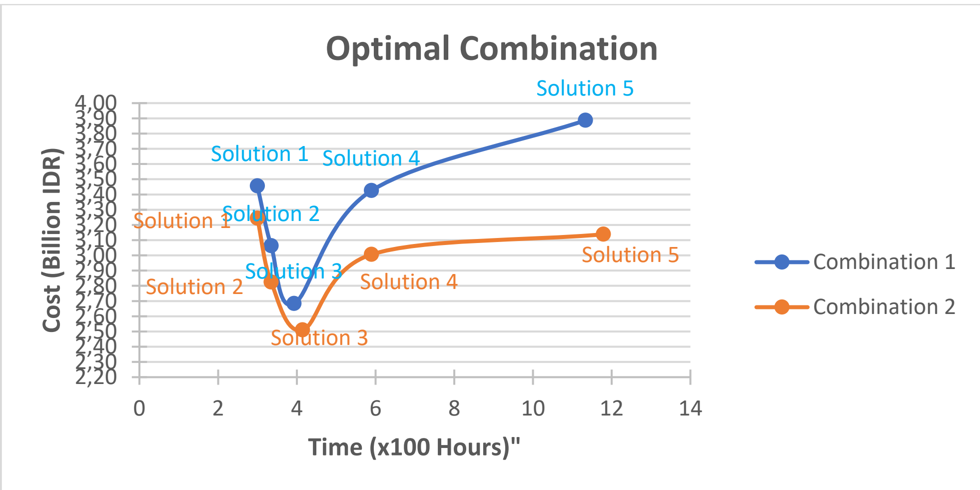

Fig. 1. Optimal Combination (Excavator KOBELCO SK 200 and Dump Truck Hino Ranger FM 260 JD)

Table 4. Summary of Optimal Cost and Time Solutions

Design Variable	Combination 1				
	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
	(5 E 8 DT)	(4 E 6 DT)	(3 E 4 DT)	(2 E 4 DT)	(1 E 2 DT)
NTP (Trucks)	8	6	4	4	2
Nle (Excavators)	5	4	3	2	1
Tip (m³)	18	18	18	18	18
Ec (m³)	0.8	0.8	0.8	0.8	0.8
Es (km/h)	15	20	30	30	35
AT (hours)	299.81	334.77	393.09	589.55	1133.41
AC (Rp)	Rp3,456,114,163.59	Rp3,062,448,304.39	Rp2,682,859,343.53	Rp3,424,808,458.12	Rp3,886,791,185.60
Design Variable	**Combination 2**				
	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
	(5 E 7 DT)	(4 E 5 DT)	(3 E 3 DT)	(2 E 3 DT)	(1 E 1 DT)
NTP (Trucks)	7	5	3	3	1
Nle (Excavators)	5	4	3	2	1
Tip (m³)	18	18	18	18	18
Ec (m³)	0.8	0.8	0.8	0.8	0.8
Es (km/h)	15	20	25	30	30
AT (hours)	299.81	334.77	414.36	589.55	1178.94
AC (Rp)	Rp3,243,124,772.69	Rp2,824,621,536.64	Rp2,510,103,428.68	Rp3,005,974,864.37	Rp3,138,348,075.37

Sensitivity Analysis. Sensitivity analysis was conducted to assess the impact of variations in dump truck speed, number of dump trucks, and number of excavators on project duration and operational cost. The goal was to identify the optimal point and efficiency boundaries of each parameter to achieve the best balance between time and cost in the earthmoving work of the IKN State Palace project. The excavator quantity sensitivity analysis showed that increasing the number of units from one to five significantly reduced project duration. However, cost efficiency did not increase proportionally. The optimal configuration was achieved with four excavators, resulting in a project duration of 293.91 hours and the lowest cost of approximately Rp2.01 billion. Adding more units beyond this point led to higher costs without proportional time savings, as illustrated in **Fig. 2**. The sensitivity analysis of dump truck quantity revealed that increasing the number of trucks from 2 to 8 significantly reduced the project duration—from 637.26 hours to 159.3 hours. However, the lowest project cost was achieved with seven dump trucks, totaling Rp2.5 billion. Excessive equipment beyond this point resulted in idle time and decreased efficiency. The optimal configuration was found with five dump trucks, offering the best trade-off between duration and cost, as shown in **Fig. 3**.

Sensitivity analysis on dump truck speed demonstrated that increasing speed from 15 km/h to 35 km/h accelerated the project duration. However, maximum cost efficiency was attained at 30 km/h. Beyond the 25–30 km/h optimal range, cost efficiency declined due to increased fuel consumption and maintenance. **Fig. 4** illustrates the sensitivity of time and cost objectives with varying truck speeds under constant conditions. These findings confirm that project efficiency is not solely achieved by adding more equipment or increasing operational speed. Instead, the optimal solution lies in balancing the number, capacity, and speed of equipment. Solution 3 in Combination 2 proved to be the most efficient, reducing project duration by 30% and cutting costs by 1.2%, thereby validating the effectiveness of the genetic algorithm approach as a decision-support tool.

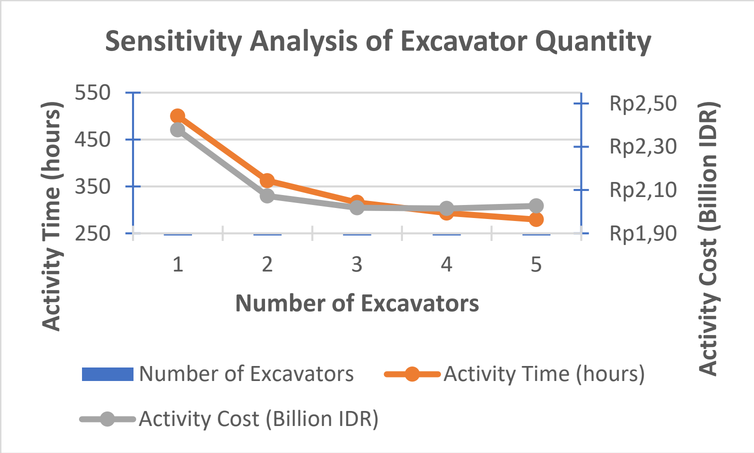

Fig. 2. Sensitivity Analysis of Excavator Quantity

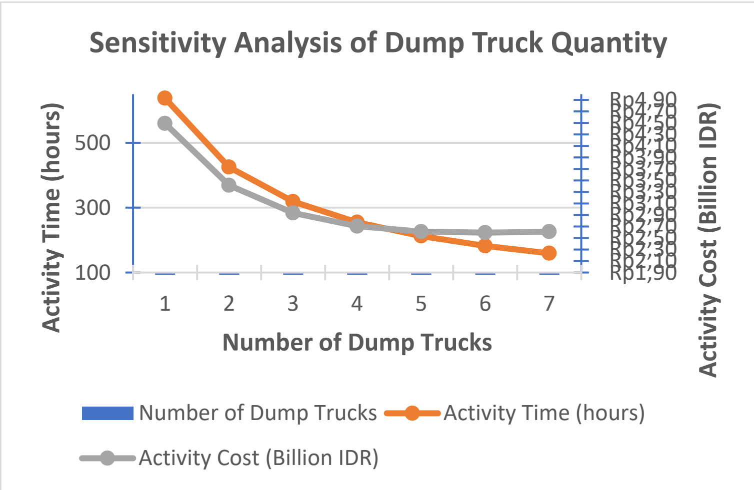

Fig. 3. Sensitivity Analysis of Dump Truck Quantity

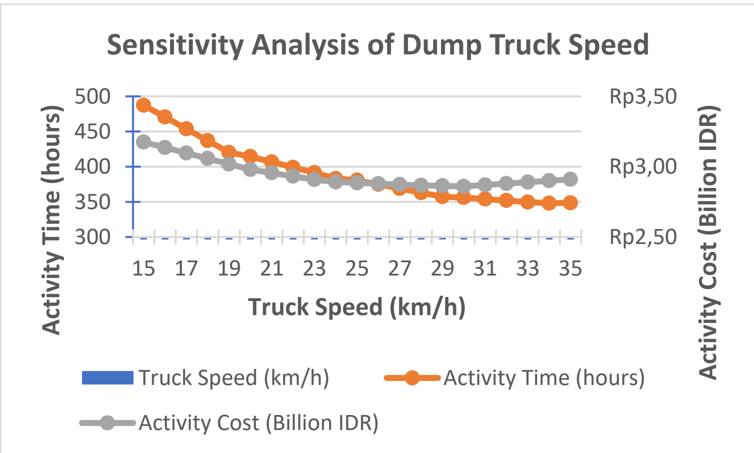

Fig. 4. Sensitivity Analysis of Dump Truck Speed

Conclusion

This study successfully developed and implemented a multi-objective optimization model using the Genetic Algorithm (GA) to determine the most efficient combination of heavy equipment—specifically excavators and dump trucks—for earthmoving activities in the construction of the Presidential Palace at Indonesia's new capital city (IKN). The model integrated technical and economic variables into two main objective functions: Activity Time (AT) and Activity Cost (AC). The optimization process revealed significant trade-offs between duration and cost across various equipment combinations. Solution 3 in Combination 2, consisting of 3 excavators and 3 dump trucks operating at 25 km/h, was identified as the optimal configuration. This setup reduced project duration by 30% and total cost by 1.2% compared to actual project implementation, making it the most balanced and efficient solution in terms of time and cost.

The sensitivity analysis further emphasized the importance of equipment quantity and operational speed. While adding more equipment generally shortened project duration, it also led to increased operational costs. Likewise, increasing truck speed reduced travel time but introduced higher fuel consumption and maintenance expenses. Therefore, the optimal strategy lies in achieving a balanced configuration that avoids both excessive underutilization and unnecessary overspending.

Compared to traditional planning methods, which often rely on manual estimates or manager intuition, the GA-based model provides a systematic and quantitative decision-making tool. This approach enables project managers and contractors to evaluate multiple alternatives, consider trade-offs, and select configurations that align with specific project goals—whether they emphasize speed, cost-efficiency, or environmental sustainability.

In conclusion, the proposed GA-based model demonstrates its effectiveness in improving resource allocation and operational planning for large-scale earthmoving projects. Its adaptability makes it a valuable asset for future infrastructure development, particularly in regions with diverse constraints and complex project dynamics.

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